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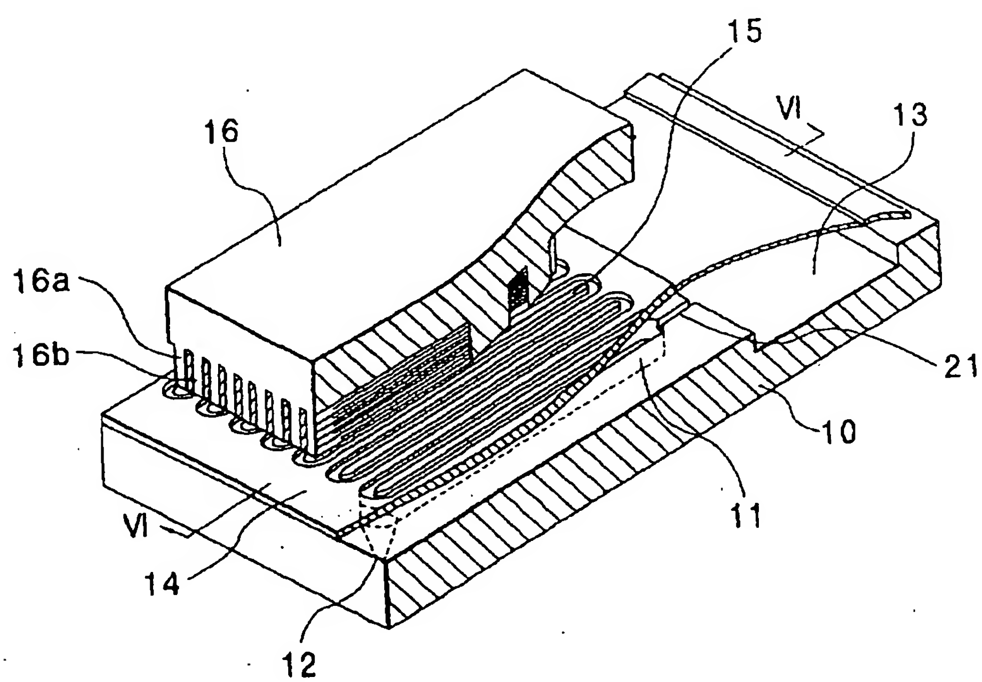
(54) Ink jet recording head controlling diameter of an ink droplet

(57) An ink jet recording head has a plurality of pressure chambers (11) each driven by a piezoelectric element (16) for ejection of ink droplets (20) having different diameters from a nozzle (12). The drive voltage for the piezoelectric element (16) has a controlled rise-time (tu), controlled pulse period (tw), and a controlled fall-time (td) for ejecting ink droplets (20) having different diameters and a constant velocity.

FIG. 5



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Description

BACKGROUND OF THE INVENTION

(a) Field of the Invention

[0001] The present invention relates to an ink jet recording head capable of controlling the diameter of an ink droplet ejected from the ink jet recording head to record a gray scale image. The present invention also relates to a method for controlling the diameter of an ink droplet in an ink jet recording head.

(b) Description of the Related Art

[0002] A drop-on-demand ink jet printer ejects ink droplets from ink nozzles of an ink jet recording head only when the ink droplets are requested. Specifically, the ink droplet is ejected from the ink nozzle by impressing a drive voltage to the piezoelectric element to generate a pressure wave in the ink chamber.

[0003] On the other hand, a stemmed ink jet recording head, such as proposed in Patent Publication JP-B-49(1974)-9622 for example, ejects ink droplets having variable diameters onto a recording sheet to thereby print a gray scale image such as for photographic data.

[0004] Fig. 1 shows a cross section of a conventional ink jet recording head, described in JP-A-51-37541, wherein a combination of a piezoelectric element 185 and a diaphragm 184 generates a pressure wave in a pressure chamber 182 of the ink jet recording head 180 receiving therein liquid ink. The pressure wave is transferred to a first nozzle 181, where the liquid ink in the ink supply chamber 183 is ejected from a second nozzle 186 due to the pressure wave while forming an ink droplet 188.

[0005] Figs. 2A and 2B show examples of dot patterns formed by the conventional ink jet recording head 180, wherein a single pixel is formed by a matrix of N×N dots 151. In Fig. 2A, the gray scale image is represented by the arrangement of a plurality of dots 151 marked in the matrix, with the diameter of the dots 151 being constant. In this configuration, the number L1 of gray scale levels are expressed by:

$$L1=N^2. \qquad (1)$$

[0006] A higher resolution and a larger number of gray scale levels, such as for a photographic image, require a larger number (N) of dots 151 for the matrix (or larger matrix size N) in Fig. 2A. The larger matrix size N also requires a higher resolution for the dot itself due to reduction in the resolution for each pixel.

[0007] On the other hand, if the dots have variable dot diameters, such as shown in Fig. 2B, the dots by themselves provide gray scale levels. Specifically, assuming that the number of gray scale levels for each dot is n, the number L2 of gray scale levels in Fig. 2B can be expressed by:

$$L2=n\times N^2 \qquad (2)$$

[0008] In the dot pattern of Fig. 2A, wherein n=1 in equation (2) due to the constant diameter of the dots 151 and N=3 for the matrix size, the number L2 of gray scale levels obtained from equation (2) is L2=9. On the other hand, in the dot pattern of Fig. 2B wherein n=4 in equation (2) due to the four levels of the variable dot diameters (151a, 151b, 151c and 151d) and N=3, the number L2 of gray scale levels obtained from equation (2) is L2=36, which is far greater compared to Fig. 2A, whereas the resolution for each pixel in Fig. 2B is not degraded. In short, the variable dot diameter pattern shown in Fig. 2B can increase the number of gray scale levels for the dot pattern without raising the dot resolution.

[0009] The control of the dot diameter can be achieved by the amount Q of ink for each ink droplet. The amount Q is expressed by:

$$Q \propto \tau \times v \times A. \qquad (3)$$

wherein τ, v and A are wave motion period of the pressure wave generated in the pressure chamber 182, velocity of the ejected ink droplet and the sectional area of the second nozzle 186, respectively. The velocity (v) of the ink droplet and drive voltage V applied to the piezoelectric element 185 have the following relationship:

$$v \propto V. \quad (4)$$

[0010] Fig. 3 shows exemplified pressure response characteristics of the ink in the pressure chamber 182, wherein the peak pressure of the ink in the pressure chamber 182 changes Pa to Pd based on the applied voltages V.
[0011] The velocity v of the ejected ink droplet changes based on the pressure, and thus based on the applied voltage, whereas the wave motion period τ does not change. Accordingly, the following relationship:

$$Q \propto V \quad (5)$$

can be obtained from relationship (3).
[0012] In the ink jet recording head shown in Fig. 1, the voltage V applied to the piezoelectric element 185 is changed so as to control the pressure of ink in the pressure chamber 182, whereby the amount Q of the ink in the ink droplet ejected from the second nozzle 186 is controlled.
[0013] It is noted that the change of the velocity v of the ejected ink droplet affects the image quality of the conventional ink jet recording head. This is caused by deviation of the position at which the ink droplet reaches the recording sheet due to the variations of the ratio of the relative velocity between the recording head and the recording sheet to the velocity of the ejected ink droplet.
[0014] In addition, when a small ink droplet is ejected, the small ink droplet generally has a lower velocity and tends to stay in the vicinity of the second nozzle, causing stains in the ink jet recording device. This problem may be solved by a recording head proposed in JP-A-51-37541, wherein an air passage 189 is provided outside the pressure chamber 182 and a third nozzle 190 is additionally provided in front of the second nozzle 186, as shown in Fig. 1.
[0015] In the illustrated example, an airflow 191 flowing out of the third nozzle 190 at a constant velocity is generated by an air pump or an air accumulator installed outside the ink jet recording head 180. The ink droplets 188 ejected from the second nozzle 186 are lead by the airflow 191, whereby any ink droplet has a velocity equivalent to the velocity of the air flow 191. This proposal may solve the problem as described above. However, the proposed ink jet recording head has larger size, complicated structure and larger weight due to provision of the air passage 189 and the air pump or accumulator.
[0016] In an alternative of the above proposal, another ink jet recording head is proposed in JP-A-61-100469, wherein it is noted that the wave motion period of the pressure wave is acoustic and inherent to the pressure chamber.
[0017] Specifically, it is noted that the amount Q of the ink in the ejected ink droplet can be controlled based on the natural period τ of the ink pressure wave while maintaining the velocity v of the ink droplet at a constant. To obtain different diameters for the ink droplets, a plurality of ink passages having different natural periods are provided in the ink jet recording head, wherein different nozzles eject respective ink droplets having different diameters. The proposed ink jet recording head has, however, drawbacks of increased head size and higher fabrication costs.
[0018] Another drop-on-demand ink jet recording head, proposed in JP-A-62-174163, has a configuration wherein one or each of a plurality of piezoelectric elements is attached to the location corresponding to the belly portion between adjacent nodes of one of waves of the natural oscillation modes of the ink in the ink passage. The piezoelectric element thus located is driven to generate a corresponding oscillation mode.
[0019] Fig. 4A shows the configuration proposed in JP-A-62-174163 as mentioned above, wherein the piezoelectric element 172 (shown by a dotted line) is located within an ink passage 171 at the location corresponding to the belly portion sandwiched between adjacent nodes of the wave of the tertiary natural oscillation mode, and Fig. 4B shows the wave of the tertiary natural oscillation mode of the ink in the ink passage 171.
[0020] The length of the piezoelectric element 172 is designed equal to the length of the portion of the ink passage 171 corresponding to the belly portion between adjacent nodes of the tertiary natural oscillation mode, and the piezoelectric element 172 is located at the belly portion 175 between these adjacent nodes 176 and 177.
[0021] The piezoelectric element 172 is driven by a drive voltage having a waveform corresponding to the tertiary natural oscillation mode, to generate a pressure wave having the tertiary oscillation mode in the ink in the ink passage 171. Thus, the pressure wave having a relatively small wavelength can eject a small ink droplet.
[0022] A quartic or higher-order natural oscillation mode can be also obtained by attaching a plurality of piezoelectric elements to the locations corresponding to the bellies of the quartic or higher-order natural oscillation mode, and driving the attached piezoelectric elements by a drive voltage having a waveform corresponding to the natural period.
[0023] The ink jet recording head thus proposed is generally suited to generate a fundamental oscillation mode and an additional higher-order oscillation mode corresponding to the location of the piezoelectric element or locations of the piezoelectric elements. That is, the proposed recording head can eject only ink droplets having two different diameters corresponding to the fundamental mode and the higher-order mode. Thus, it is not suited to print a gray scale image having a larger number of gray scale levels, such as for photographic image.

[0024] Some other recording heads eject a plurality of smaller size ink droplets at a single position, whereby a plurality of gray scale levels are obtained by selecting the number of the ink droplets ejected at the single position. In this configuration, however, a high-speed printing is not achieved due to the iterated ejection of the ink droplets at the single position.

SUMMARY OF THE INVENTION

[0025] It is an object of the present invention to provide an ink jet recording head capable of controlling the diameter of an ink droplet and suitable for printing gray scale images in a full-color printing.

[0026] It is another object of the present invention to provide a method for controlling the diameter of an ink droplet in an ink jet recording head.

[0027] The present invention provides an ink jet recording head comprising a plurality of pressure chambers each for receiving therein ink, each of the pressure chambers having a movable wall and a fundamental period of the ink in the pressure chamber, an ink nozzle disposed for each of the pressure chambers for ejecting the ink in the pressure chamber as an ink droplet, an ink inlet port for receiving the ink to each of the pressure chambers, a piezoelectric element disposed in association with each the movable wall for responding to a drive pulse having a rise-time, a fall-time and a peak voltage, the piezoelectric element moving the corresponding movable wall to generate a pressure wave in the ink in a corresponding one of the pressure chambers, and a drive circuit for controlling at least the rise-time and the peak voltage to allow the ink nozzle to generate ink droplets having different diameters.

[0028] The present invention also provides a method for driving a ink jet recording head having a plurality of pressure chambers each for receiving therein ink, each of the pressure chambers having a movable wall and a fundamental period of the ink in the pressure chamber, a piezoelectric element disposed in association with each the movable wall for responding to a drive pulse having a rise-time, a fall-time and a peak voltage, the piezoelectric element moving the corresponding movable wall to generate a pressure wave in the ink in a corresponding one of the pressure chambers, the method comprises the step of controlling at least the rise-time and the peak voltage to allow the ink nozzle to generate ink droplets having different diameters.

[0029] In accordance with the present invention, ink droplets having different diameters can be ejected from the ink nozzle by controlling the rise-time and the peak voltage of the drive pulse for the piezoelectric element while maintaining a constant velocity of the ink droplets, which achieves a high-speed printing as well as a high-quality printing.

[0030] The above and other objects, features and advantages of the present invention will be more apparent from the following description, referring to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031]

Fig. 1 is a sectional view of a conventional ink jet recording head;
Figs. 2A and 2B are schematic views of N×N matrix dot patterns;
Fig. 3 is a timing chart of pressure waveforms of ink in an ink passage;
Fig. 4A is a longitudinal-sectional view of an ink passage, and Fig. 4B is a graph for showing one of the waves of natural oscillation modes of ink in the ink passage of Fig. 4A;
Fig. 5 is a partially-broken perspective view of an ink jet recording head according to an embodiment of the present invention;
Figs. 6A and 6B are longitudinal-sectional views of the recording head taken along line VI-VI in Fig. 5 for showing the operation of the movable waU;
Fig. 7 is a circuit diagram of the drive circuit for the ink jet recording head of Fig. 5;
Fig. 8 is a timing chart of signal waveforms in the ink jet recording head of Fig. 5;
Fig. 9 is timing chart of a pressure wave in the ink jet recording head of Fig. 5;
Figs. 10A and 10B are partial side views of the ink jet recording head of Fig. 5 for showing ink ejection.
Figs. 11A, 11B and 11C are timing charts of velocity response of the ink to the drive voltage waveform, obtained by simulations for the ink jet recording head of Fig. 5;
Fig. 12 is a timing chart of drive voltage waveforms in the ink jet recording head of Fig. 5;
Figs. 13A, 13B and 13C are partial side views of the ink jet recording head of Fig. 5 for showing ink ejection;
Fig. 14 is a schematic chart for showing the relationship between displacements of the movable blade and lengths of elongate ink droplets in the ink jet recording head of Fig. 5; and
Fig. 15 is a graph showing rise-time dependency of diameter of the ink droplet.

PREFERRED EMBODIMENTS OF THE INVENTION

[0032] In a preferred embodiment of the present invention, if waveform (drive voltage waveform) of the drive pulse has a rise-time (tu) which is between half the fundamental period (T) of the ink in the ink passage (or pressure chamber) and the fundamental period T (i.e., $T/2 \leqq tu \leqq T$), the pulse duration (tw) defined between the start of the rise-time (tu) and the start of the fall-time (td) is set at the fundamental period (T), and the peak voltage Vp of the drive voltage waveform is determined as $Vp = tu \times V0/t0$, wherein t0 and V0 are such that a suitable speed can be obtained by a specific peak voltage V0 with a rise-time of t0, which is equal to T/2, for a specific diameter of the ink droplet. In short, the peak voltage is controlled so that the peak voltage Vp is proportional to the rise-time tu for different diameters of the ink droplets.

[0033] If the rise-time tu is determined as $0 \leqq tu \leqq T/2$, the pulse duration tw is set at the fundamental period T, and the peak voltage Vp is determined as:

$$Vp = 2 \times tu \times V0/T \times \sin(\pi \times tu/T),$$

wherein V0 is determined such that a suitable velocity can be obtained by a specific peak voltage V0 with a rise-time equal to T/2.

[0034] If the rise-time tu is determined as $T \leqq tu$, the pulse duration tw is set at an integral multiple of the fundamental period T, and the peak voltage Vp is determined such that Vp/tu is equal to V0/t0 wherein a peak voltage V0 is obtained at t0 during the rise-time.

[0035] In the above conditions, the fall-time td of the drive voltage waveform is determined equal to the rise-time tu or longer, to form a trapezoid or triangle of the overall drive waveform. A desired diameter of the ink droplet can be obtained by controlling the rise-time tu and the peak voltage Vp without involving variations in the velocity of the ejected ink droplets.

[0036] Now, the present invention is more specifically described with reference to accompanying drawings.

[0037] Referring to Fig. 5, an ink jet recording head, generally designated by 100, according to an embodiment of the present invention includes a bottom plate 10, a plurality of pressure chambers 11 extending in the longitudinal direction of the ink jet recording head and each having side walls and a bottom wall defined by the bottom plate 10, and an elastic plate 14 adhered to the bottom plate 10 for covering the pressure chambers 11.

[0038] The elastic plate 14 has a movable wall 15 at the top of each pressure chamber 11. Each pressure chamber 11 has an ink nozzle 12 at the bottom thereof in the vicinity of the front end of the each pressure chamber 11, and an ink inlet port 32 formed in the rear wall of the pressure chamber and communicated with an ink reservoir 13 formed at the rear side of the bottom plate 10. A piezoelectric element 16 is provided on the top of the elastic plate 14.

[0039] The piezoelectric element 16 has a plurality of movable blades 16a and a plurality of support blades 16b separated by cutout grooves (shown by hatching in the figure) and alternately disposed with each other. The movable blade 16a is bonded to a corresponding movable wall 15 of the elastic plate 14. The support blade 16b is boned to the stationary portion of the elastic plate 14 at the space between adjacent movable walls 15.

[0040] In the above configuration, when the movable blade 16a of the piezoelectric element 16 is impressed with a drive voltage, the movable blade 16a expands toward the bottom plate 10 to deform the movable wall 15, which protrudes in the pressure chamber 11 to raise the pressure in the pressure chamber 11.

[0041] The support blades 16b are provided to limit the movement of the elastic plate 14, whereby only the movable walls 15 of the elastic plate 14 expand downward and the overall structure of the recording head 100 including the bottom plate 10 and the remaining portions of the elastic plate 14 is not affected by the deformation of the movable blades 16a. The support blade 16b thus prevents the nozzles 12 adjacent to the driven nozzle 12 from ejecting ink droplets, thereby removing the cross talk between the nozzles 12. The problem cross talk can be also removed by a configuration such as proposed in JP-A-9-174837.

[0042] Referring to Figs. 6A and 6B, there are shown states of one of the pressure chambers 11 and an associated movable blade 16a of the piezoelectric element 16. Fig. 6A shows a stationary state wherein no drive voltage is applied, whereas Fig. 6B shows a state wherein the movable blade 16a is driven by a drive puse supplied from the drive circuit 19. The piezoelectric element 16 includes a pair of first and second comb-shaped electrodes 17a and 17b each including a plurality *of* electrode layers in each of the movable blades 16a and the support blades 16b, with a corresponding pair of layers 17 and 17b opposed to each other. The piezoelectric element 16 has also a plurality of piezoelectric layers 18 each sandwiched between a corresponding pair of opposed electrode layers 17a and 17b. Each piezoelectric layer 18 has a thickness of tens of micrometers, for example. The first electrode 17a of the movable blade 16a is applied with a drive voltage by the drive circuit 19, whereas the second electrode 17b is grounded. On the other hand, the electrodes of the support blade 16b are isolated from outside. The specified configuration of the piezoelectric element 16 allows an effective displacement of the movable blades 16a when applied with a relatively low voltage as

low as tens of volts, with the support blades 16b maintained at a stationary state.

[0043] When a drive voltage is applied from the drive circuit 19, the piezoelectric element 16 is deformed, whereby the movable wall 15 is warped to protrude downward inside the pressure chamber 11 by the thrust force of the movable blade 16a, as shown in Fig. 6B. As a result, a pressure wave is generated in the ink in the ink chamber 11. The pressure wave in the ink is transferred to the ink nozzle 12, which ejects an ink droplet 20 therefrom.

[0044] Referring to Fig. 7, the drive circuit 19 disposed for the ink jet recording head 100 includes a common circuit section 51 for impressing a drive voltage Vd to a common line connected to all the movable blades 16a and a switch 53 disposed for a corresponding one of the movable blades 16a. The switch 53 connects the corresponding movable blade 16a to the ground for impressing the drive voltage to the corresponding movable blade 16a, thereby applying an impulse wave 31 to the pressure chamber 11.

[0045] The common circuit section 51 includes a signal generator 52 including a charge pulse section 52a for generating a charge pulse Va and a discharge pulse section 52b for generating a discharge pulse Vb, a pair of cascaded NPN transistors 61 which are turned on by the charge pulse Va for charging the common line to a source voltage +V, and a pair of cascaded NPN transistors 62 which are turned on by the discharge pulse Vb for discharging the common line to the ground potential.

[0046] Referring to Fig. 8, after the switch circuits 53 latch the input print dot data, a charge pulse Va having a first duration tu is supplied from the charge pulse section 52a to the cascaded transistors 61. Thus, the cascaded transistors 61 charges the common line (Vd) up to the source potential +V during the first duration (rise-time) tu to deform the desired movable blade 16a, thereby applying an impulse wave 31.

[0047] After a second duration tw (tw>tu) elapsed since the start of the charge pulse Va, the discharge section 52b supplies a discharge pulse Vb having a third duration td to the cascaded transistors 62, to discharge the common line (Vd) down to the ground potential during the fall-time td. Thus, by controlling the timing of the charge pulse Va and the discharge pulse Vb, a desired waveform of the drive pulse Vd can be obtained as shown in Fig. 8, the drive pulse Vd including a rising edge 30u, a platform 30 and a falling edge 30d. Since the response time of the piezoelectric element is small and negligible, the waveform of the drive pulse Vd can be regarded as the deformation or displacement itself of the movable wall 15 shown in Fig. 6B.

[0048] The magnitude of the pressure in the pressure chamber 11 and the ink ejection velocity can be determined by the slope of the rising edge 30u and the falling edge 30d of the drive voltage Vd or the deformation velocity of the movable wall 15.

[0049] Assuming that the drive voltage Vd has a uniform slope at the rising edge 30u and the falling edge 30d, the impulse wave 31 includes rectangular pulses 31a and 31b having first duration (equal to rise-time) tu and the third duration (equal to fall-time) td, respectively.

[0050] The velocity response v of the nozzle receiving the rectangular pulses 31a and 31b are as follows, The waveform ξ (t) of the rectangular pulses can be expressed by:

$$\xi(t) = \xi u, \quad \text{for a time interval t: } 0 \leqq t \leqq t \tag{6}$$

$$\xi(t) = 0, \quad \text{for a time interval t: } tu \leqq t \leqq tw) \tag{7}$$

$$\xi(t) = \xi d, \quad \text{for a time interval t: } tw \leqq t \leqq tw+td \tag{8}$$

$$\xi(t) = 0, \quad \text{for a time interval t: } tw+td \leqq t) \tag{9}$$

wherein ξ u and ξ d are the maximum values of the pulse.

[0051] The velocity response v(t) can be expressed as follows:

$$v1(t) = \alpha \times \xi u \times (1-\cos \omega_n t) \quad \text{for } 0 \leqq t \leqq tu \tag{10}$$

$$v2(t) = \alpha \times \xi u \times \{2\sin(\pi\, tu/T)\} \times \sin\omega_n(t-tu/2)$$

$$\text{for } 0 \leqq t \leqq tw \tag{11}$$

$$v3(t)=v2(t)+\alpha \times \xi d \times (1-\cos\omega_n t)$$

$$\text{for } 0 \leqq t \leqq td \quad (12)$$

$$v4(t)=v2(t)+\alpha \times \xi d\{2\sin(\pi\, td/T)\} \times \sin\omega_n(t-tw-td/2)$$

$$\text{for } tw+td \leqq t \quad (13)$$

wherein α represents a coefficient for converting the peaks of the rectangular pulses 31a and 31b into the ink velocity v(t), and can be determined based on the ink density, volume modulus and shape and dimensions of the pressure chamber, whereas ω_n represents natural angular frequency and is expressed by $2\pi/T$ where T is the fundamental period of the ink in the pressure chamber.

[0052] Referring to Fig. 9, there is shown a timing chart of the pressure wave which corresponds to the velocity response characteristic of the ink at the nozzle 12. The hatched area, obtained by integration of the first positive pressure wave 41 (or integration of the velocity response curve 41), corresponds to the length L1 of an elongate ink droplet, such as 44 shown in Fig. 10A, which is just ejected from the nozzle. The elongate ink droplet 44 is separated from the succeeding ink droplet due to the presence of the succeeding negative pressure wave 42. The elongate ink droplet 44 has a volume calculated by multiplying the hatched area in Fig. 9 by the sectional area of the nozzle. The elongate ink droplet 44 is formed as a spherical main ink droplet 45 after the ejection, as shown in Fig. 10B.

[0053] A satellite ink droplet 46 is further ejected following the main ink droplet 45 due to the succeeding positive wave 43 in Fig. 9 generated by the residual vibration, as shown in Fig. 10B.

[0054] The satellite ink droplet 46 has a lower velocity compared to the main ink droplet 45, thereby degrading the image quality of the ink jet recording head. Thus, the residual vibration should be removed or controlled for improving the image quality.

[0055] To control the residual vibration of the ink after impressing the drive voltage, it is noted from equation (13) that rise-time tu, fall-time td and pulse duration tw of the drive voltage waveform should satisfy the following equation:

$$v4(t)=0 \quad (14)$$

[0056] Assuming that rise-time tu and fall-time td are equal, which results in $\xi u=\xi d$, the following relationship:

$$\sin\omega_n(t-tu/2)=\sin\omega_n(t-tw-tu/2) \quad (15)$$

can be obtained from equations (13) and (14).
Further, from equation (15), utilizing the nature of the sine function, the following relationship:

$$tw=n \times T$$

can be obtained where n=1, 2, 3, ···. This means that the residual vibration can be suppressed when the rise-time tu is equal to the fall-time td and the pulse duration tw is an integral multiple of the natural vibration period (fundamental period) T of the ink in the pressure chamber 11.

[0057] In a practical configuration, considering that the velocity response of ink to the pressure wave exhibits attenuation due to viscosity of the ink, the equality of the rise-time tu and the fall-time td may be modified so that the fall-time td is slightly longer than the rise-time tu.

[0058] The volume of the ink droplet can be controlled by changing the rise-time tu and the fall-time td of the drive voltage waveform under the condition as described above. The volume of the ink droplet is approximately equal to the product of the maximum displacement of the movable wall by the sectional area of the nozzle, the displacement being obtained by integration of the velocity of the ink droplet just ejected from the nozzle with respect to time (see journal of ELECTROPHOTOGRAPHIC INSTITUTE, 1987, March vol. 26-1, pp2-10, for example). A larger volume for the ink droplet can be obtained by a larger rise-time tu of the drive voltage in equation (10) compared to the fundamental period T of the ink.

[0059] Figs. 11A, 11B and 11C show results of simulation of the velocity response of the ink to the drive voltage

waveform for the ink jet recording head according to the embodiment. Fig. 8 shows the practical examples of the drive voltage waveform, which were used for the simulations. A finite element method is used in the simulations.

[0060] The waveforms 21e and 22e are of a trapezoid due to a smaller rise-time tu compared to the fundamental period T, whereas the waveform 23e is of a triangle due to the coincidence of the pulse duration tw with the fundamental period T and an equality of rise-time tu with the fundamental period T.

[0061] The simulations for the case, wherein drive voltage waveforms 21e and 23e were applied to the piezoelectric element, revealed velocity responses 21v and 23v shown in Fig. 11A. The rise-time tu in waveform 21e, which is smaller than half the fundamental period T, presented a peak of velocity response 21v which is smaller than the peak of velocity response 23v when the slope of waveform 21e is equal to the slope of waveform 23e. Thus, a larger slope in the rise-time tu of waveform 21e should be employed to correct the peak voltage Vp so that the peak of velocity response 21e is equal to the peak of velocity response 23e. The correction can be expressed based on equation (11) as follows:

$$Vp= (2V0 \times tu/T)/\sin \pi\ tu/T \qquad (17)$$

wherein V0 represents a peak voltage when the drive voltage waveform has a rise-time tu=T/2. Under this condition, the ink velocity is at a maximum and called a basic velocity.

[0062] Corrected velocity response 21v provided by the corrected drive voltage waveform 21e has a smaller wavelength compared to velocity response 23v and thus provides a smaller volume for the ink droplet. On the other hand, the peak of velocity response 21v is equal to the peak of velocity response 23v, which means a smaller volume can be obtained without reducing the ink velocity.

[0063] In Fig. 12, drive voltage waveform 24e, 25e and 26e have rise-times tu which are larger than the fundamental period T. Thus, the pulse widths tw are set at a value which is double the fundamental period T based on equation (16).

[0064] On the other hand, drive voltage waveforms 27e, 28e and 29e have rise-times tu which are larger than double the fundamental period T. Thus, the pulse widths tw are set at a value equal to twice the fundamental period T.

[0065] The simulations for drive voltage waveforms 26e and 28e are shown in Fig. 11B. The drive voltage waveform 26e having a rise-time tu equal to double the fundamental period T provided a first velocity wave 26v and a second velocity wave 26v'.

[0066] Fig. 13A, 13B and 13C show the ink droplets ejected by the drive voltage waveforms 23e, 26e and 29e, respectively. In Fig. 13B, the first wave 26 and the second wave 26v' ejected a main droplet 26m and an accompanying droplet 26s, respectively, which are coupled together to form a single droplet 26m' by a surface tension. The coupled droplet 26m' has a larger volume compared to the droplet 23m' shown in Fig. 13A.

[0067] The drive voltage waveform 29e having a rise-time tu larger than double the fundamental period T provides a third wave 29v" in addition to the first and second waves 29v and 29v', as shown in Fig. 11C. The time intervals between the first wave and the third wave is extremely small compared to the velocity of the droplets. These waves eject a main droplet 29m, a first accompanying droplet 29s1 and a second accompanying droplet 29s2, as shown in Fig. 13C. Although the velocity of the second accompanying droplet 29s2 is smaller compared to those of the main droplet 29m and the first accompanying droplet 29s1, these three droplets are coupled together by a surface tension to form a larger single droplet 29m'.

[0068] In the present embodiment, there is an advantage in that a larger maximum size of the ink droplet does not involve a reduced printing velocity. In contrast, in the conventional recording head, a larger ink droplet is obtained by a larger wavelength for a single pressure wave, which required a larger fundamental period T and thus necessitated a longer ink passage.

[0069] More specifically, for example, after the ink droplet 20 is ejected from a nozzle 12 in Fig. 6B, the ink in the pressure chamber 11 for the nozzle 12 is consumed. Thus, the consumed amount of ink is then replenished from the ink reservoir 13 through the pressure chamber 11 to the nozzle due to the surface tension of the ink meniscus in the nozzle 12 and a capillary function.

[0070] If the pressure chamber 11 has a larger length, the ink replenishment takes a long time due to a larger resistance in the pressure chamber 11 resulting from the viscosity of the ink. In contrast, in the present embodiment, the maximum diameter of the ink droplet depends on the displacement of the piezoelectric element irrespective of the length of the pressure chamber. Thus, a large ink droplet can be ejected from a pressure chamber having a smaller length.

[0071] The smaller length of the pressure chamber reduces the viscose resistance of the ink, and accelerates the ink replenishment after the ink ejection. As a result, a repetitive frequency for the in ejection can be improved in the present embodiment to achieve a higher-speed printing compared to the conventional recording head.

[0072] Referring to Fig. 14, there is shown length of the elongate ink droplet responding to the drive voltage. Fig. 14 can be obtained by integration of the waveforms of velocity shown in Figs. 11A, 11B and 11C with respect to time, thereby showing the lengths L of the elongate ink droplets (just after ejected from the nozzle) which correspond to the

displacements based on the drive voltages 21e to 29e shown in Fig. 12.

[0073] The products of the maximum values 21L to 29L for the respective response waveforms 21c to 29c by the sectional area of the nozzle correspond to the volumes of the ink droplets. If the maximum voltage for the piezoelectric element is obtained by the drive voltage waveform 29e due to the limit by the source voltage, the maximum length of the elongate ink droplet is 29L. On the other hand, if the minimum voltage is provided by the drive voltage waveform due to the characteristics of the piezoelectric element, the minimum length of the elongate ink droplet is 21L.

[0074] Referring to Fig. 15, there is shown rise-time dependency of the diameter of ink droplet. The diameters 21d to 29d are obtained by multiplying the maximum values of the response curves of Fig. 10 by the sectional area of the nozzle, correcting the obtained values into diameters of the ink droplets, and plotting the same with respect to the rise-times tu of the respective drive voltage waveforms 21e to 29e.

[0075] If the rise-time in the drive voltage waveform resides in the vicinity of integral multiples of the fundamental period T, the increase of the displacement for the ink ejection is lowered in the vicinity, as shown at the portions in the vicinities of 23d, 26d and 29d in the curve of Fig. 11, corresponding to the drive voltage waveforms 23e, 26e and 29e.

[0076] Although the obtained results, as shown in Fig. 12, do not exhibit a linear relationship between the dot diameter and the rise-time, the dot diameter can be controlled substantially linearly by retrieving the correcting factor for the rise-time based on the input data from a table.

[0077] The present invention can be applied, in addition to the piezoelectric element having a laminate structure as described above, to an impulse ink jet recording head using a birnorph piezoelectric element and an impulse applied to the ink in the recording head.

[0078] The present invention can be also applied to an ink jet recording head using a lower concentration ink in addition to a normal ink to adapt to a gray scale printing using different concentrations of ink in combination with the minimum diameter droplet.

[0079] Since the above embodiments are described only for examples, the present invention is not limited to the above embodiments and various modifications or alterations can be easily made therefrom by those skilled in the art without departing from the scope of the present invention.

Claims

1. An ink jet recording head comprising a plurality of pressure chambers (11) each for receiving therein ink, each of said pressure chambers (11) having a movable wall (15) and a fundamental period (T) of the ink in said pressure chamber (11), an ink nozzle (12) disposed for each of said pressure chambers (11) for ejecting the ink in said pressure chamber (11) as an ink droplet (20), an ink inlet port (32) for receiving the ink to each of said pressure chambers (11), a piezoelectric element (16) disposed in association with each said movable wall (15) for responding to a drive pulse having a rise-time (tu), a fall-time (td) and a peak voltage (Vp), said piezoelectric element (16) moving said corresponding movable wall (15) to generate a pressure wave in the ink in a corresponding one of said pressure chambers (11), characterized by:

   a drive circuit (19) for controlling at least said rise-time (tu) and said peak voltage (Vp) to allow said ink nozzle (12) to generate ink droplets (20) having different diameters.

2. The ink jet recording head as defined in claim 1, wherein said rise-time (tu) is above half said fundamental period (T), and a pulse duration (tw) between a start of said rise-time (tu) and a start of said fall-time (td) is equal to said fundamental period (T).

3. The ink jet recording head as defined in claim 2, wherein said rise-time (tu) is below said fundamental period (T), and said peak voltage (Vp) is proportional to said rise-time (tu).

4. The ink jet recording head as defined in claim 3, wherein said rise-time (tu) is substantially equal to said fall-time (td).

5. The ink jet recording head as defined in claim 4, wherein said drive pulse is of a trapezoid or a triangle, and said rise-time (tu) has a constant slope for said ink droplets (20) having different diameters.

6. The ink jet recording head as defined in claim 2, wherein said rise-time (tu) is above said fundamental period (T), and is an integral multiple of said fundamental period (T).

7. The ink jet recording head as defined in claim 6, wherein said rise-time (tu) is substantially equal to said fall-time (tu).

8. The ink jet recording head as defined in claim 7, wherein said drive pulse is of a trapezoid or a triangle, and said

rise-time (tu) has a constant slope for said ink droplets having different diameters.

9. The ink jet recording head as defined in claim 1, wherein said rise-time (tu) is below half said fundamental period (T).

10. The ink jet recording head as defined in claim 9, wherein a pulse duration (tw) between a start of said rise-time (tu) and a start of aid fall-time (td) is equal to said fundamental period (T).

11. The ink jet recording head as defined in claim 10, wherein said rise-time (tu) is substantially equal to said fall-time (td).

12. The ink jet recording head as defined in claim 11, wherein said drive pulse is of a trapezoid or a triangle, and said rise-time (tu) has a constant slope for said ink droplets (20) having different diameters.

13. A method for driving a ink jet recording head having a plurality of pressure chambers (11) each for receiving therein ink, each of said pressure chambers (11) having a movable wall (15) and a fundamental period (T) of the ink in said pressure chamber (11), a piezoelectric element (16) disposed in association with each said movable wall (15) for responding to a drive pulse having a rise-time (tu), a fall-time (td) and a peak voltage (Vp), said piezoelectric element (16) moving said corresponding movable wall (15) to generate a pressure wave in the ink in a corresponding one of said pressure chambers (11), said method characterized by the step of controlling at least said rise-time (tu) and said peak voltage (Vp) to allow said ink nozzle (12) to generate ink droplets (20) having different diameters.

14. The method as defined in claim 13, wherein said rise-time (tu) is above half said fundamental period (T), and a pulse duration (tw) between a start of said rise-time (tu) and a start of said fall-time (td) is equal to said fundamental period (T).

15. The method as defined in claim 14, wherein said rise-time (tu) is below said fundamental period (T), and said peak voltage (Vp) is proportional to said rise-time (tu9.

16. The method as defined in claim 13, wherein said rise-time (tu) is above said fundamental period (T), and is an integral multiple of said fundamental period (T).

17. The method as defined in claim 16, wherein said drive pulse is of a trapezoid or a triangle, and said rise-time (tu) has a constant slope for said ink droplets (20) having different diameters.

18. The method as defined in claim 13, wherein said rise-time (tu) is below half said fundamental period (T).

19. The method as defined in claim 18, wherein said drive pulse is of a trapezoid or a triangle, and said rise-time (tu) has a constant slope for said ink droplets (20) having different diameters.

FIG. 1
PRIOR ART

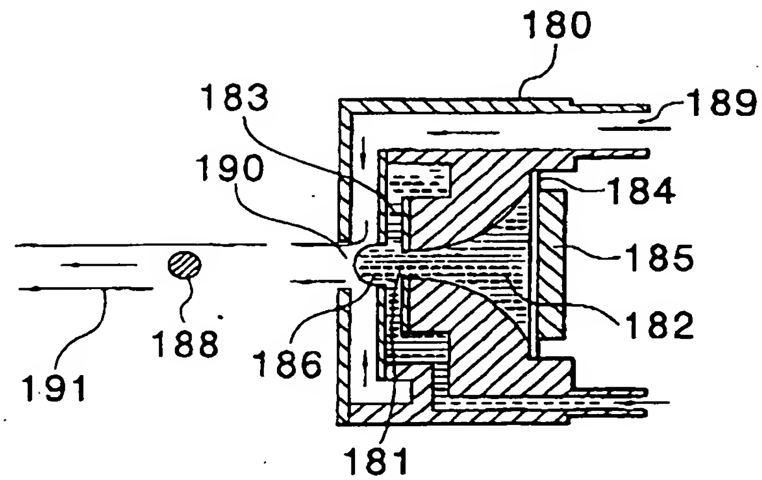


FIG. 2A
PRIOR ART

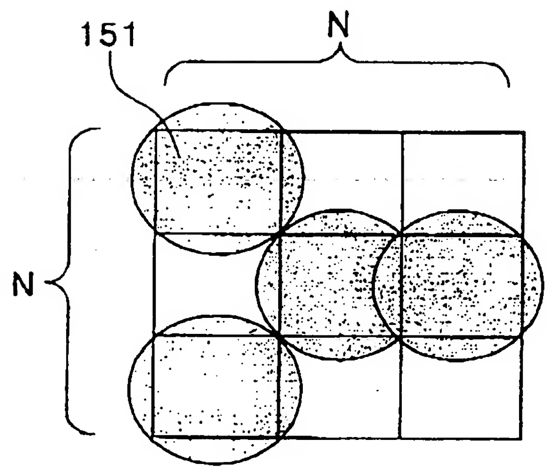


FIG. 2B
PRIOR ART

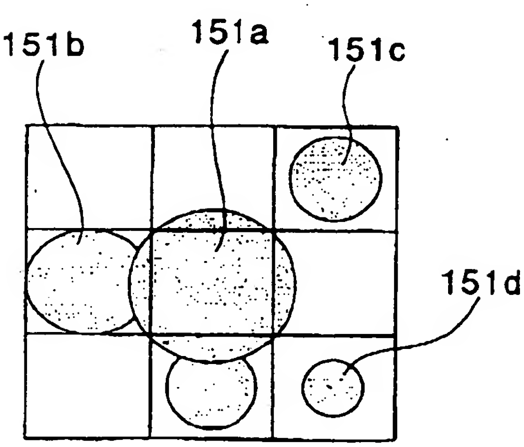
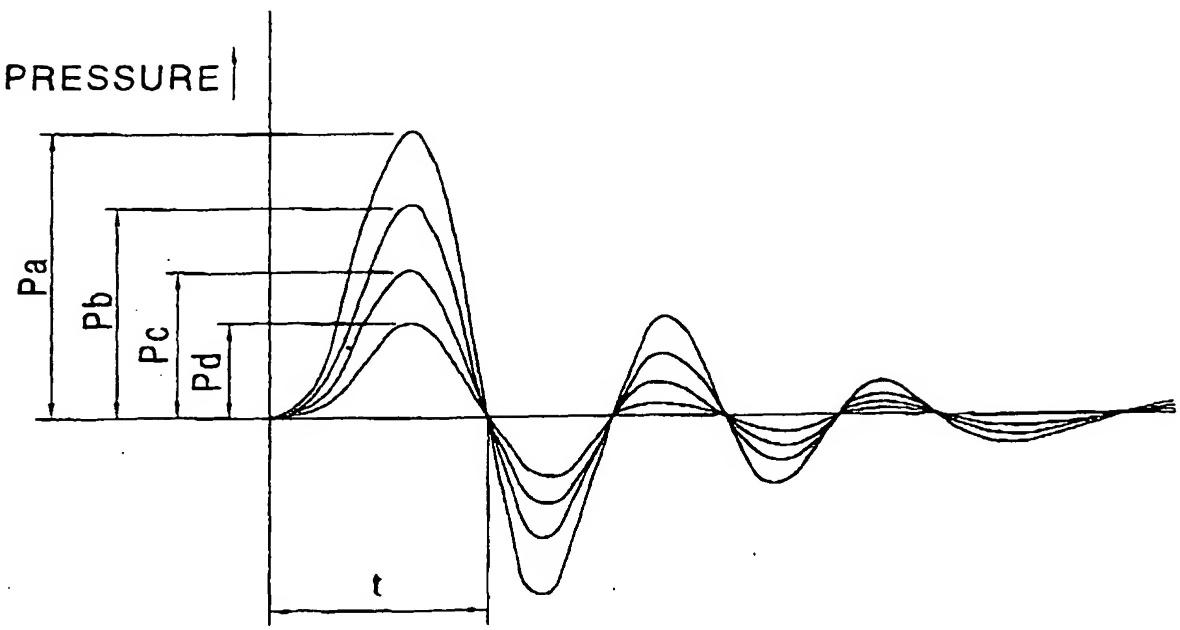


FIG. 3
PRIOR ART



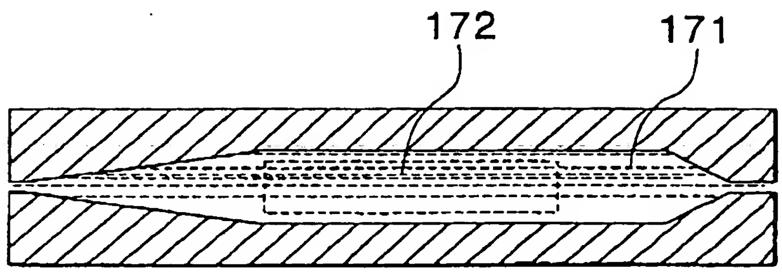


FIG. 4A
PRIOR ART

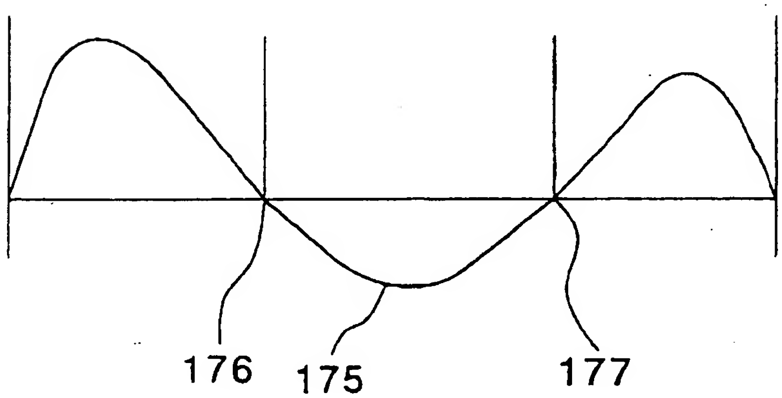


FIG. 4B
PRIOR ART

FIG. 5

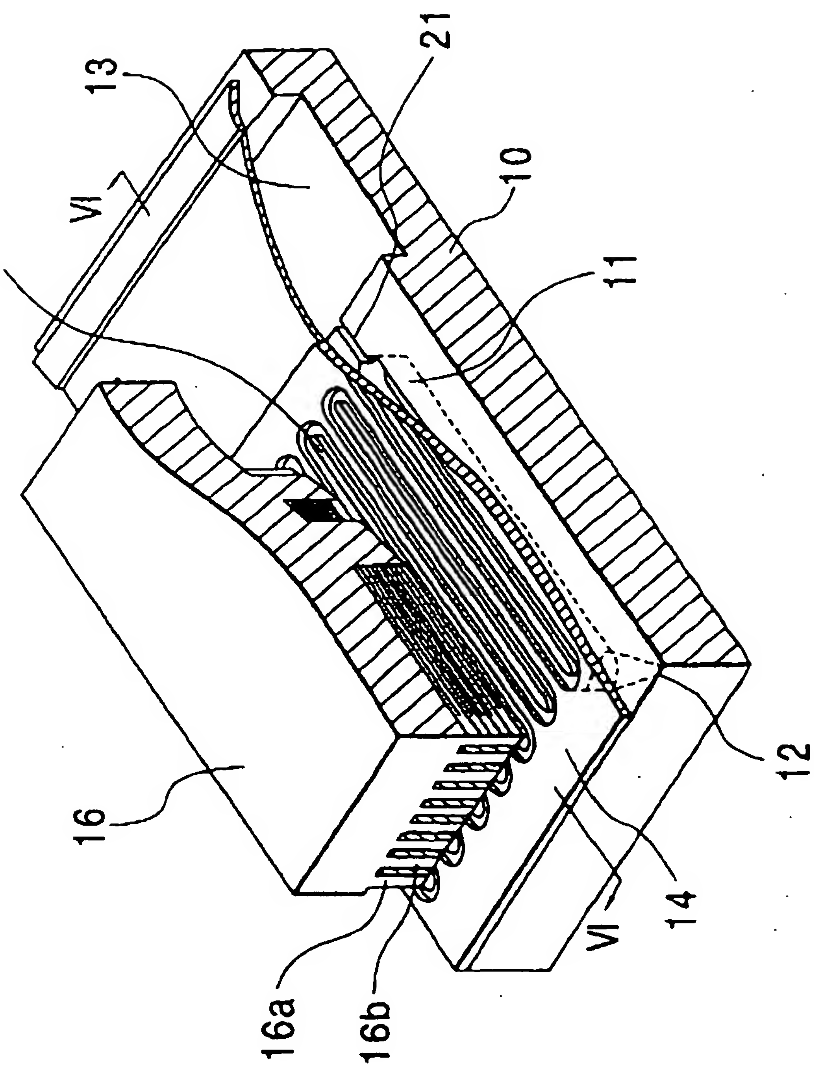


FIG. 6A

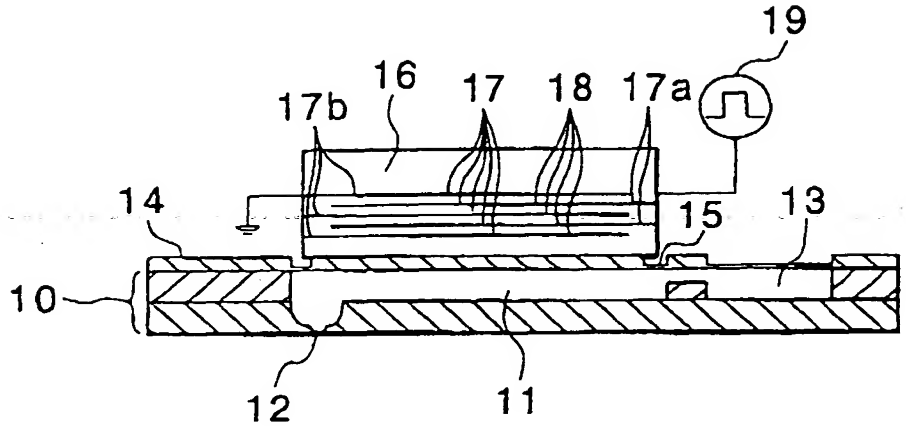


FIG. 6B

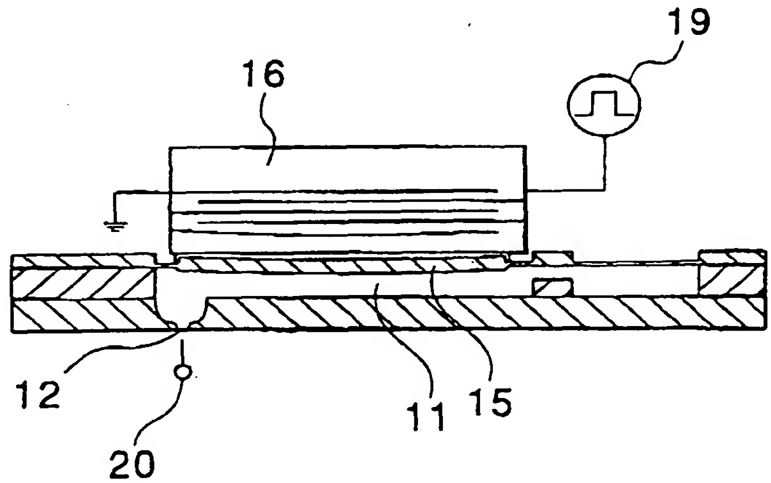


FIG. 7

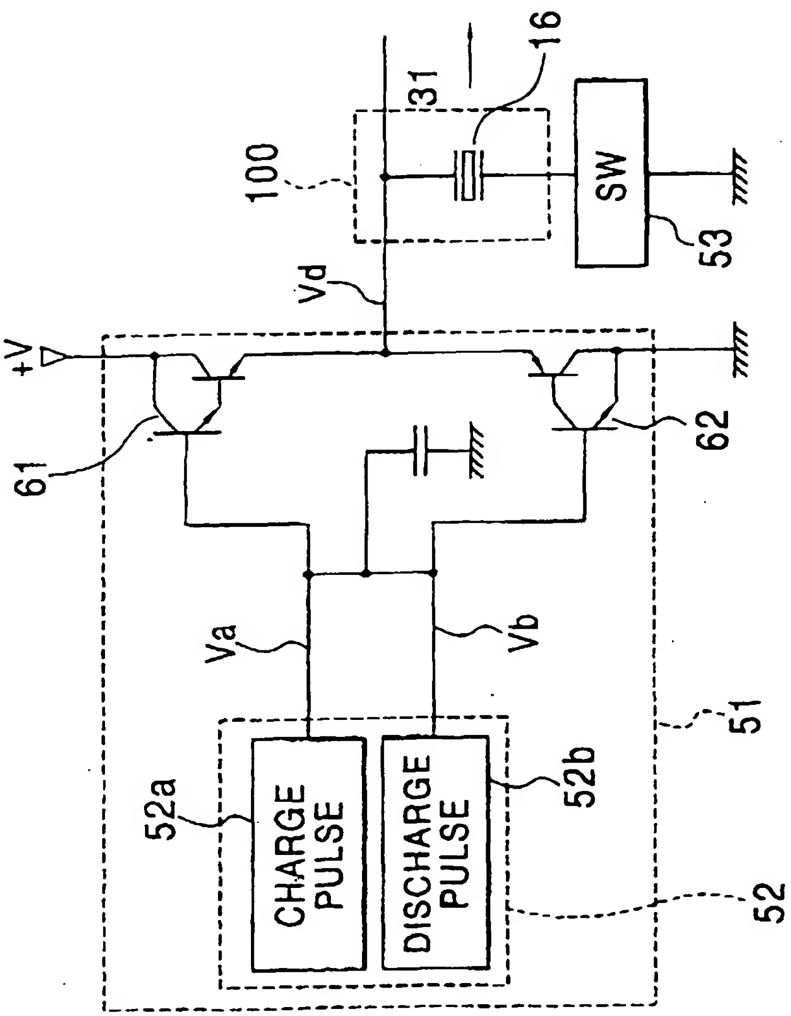

+V
61
62
Vd
100
31
16
SW
53
Va
Vb
CHARGE PULSE
DISCHARGE PULSE
52a
52b
52
51

FIG. 8

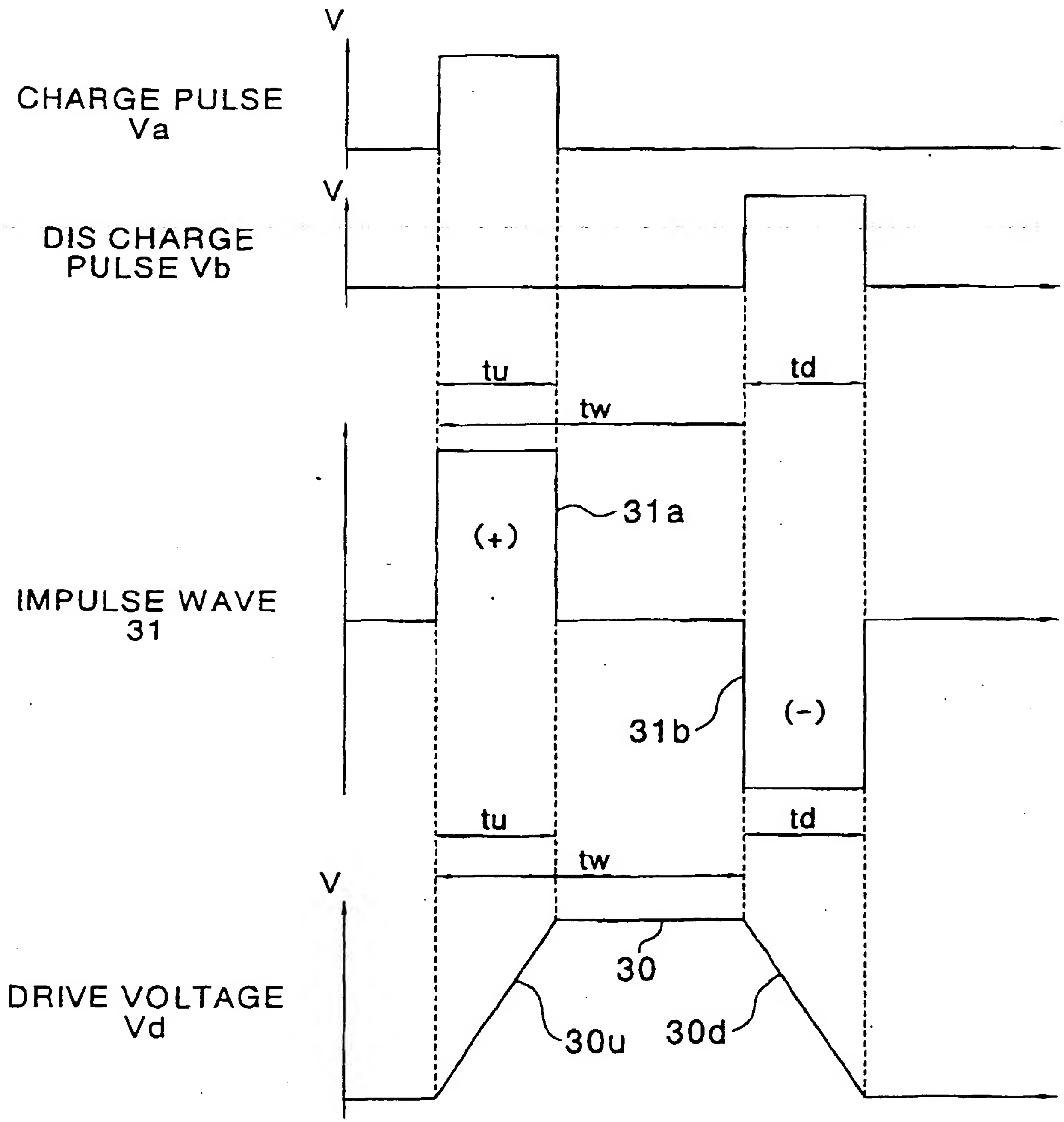

V
CHARGE PULSE
Va
V
DIS CHARGE
PULSE Vb
tu
td
tw
31a
(+)
IMPULSE WAVE
31
31b
(-)
tu
td
tw
V
30
DRIVE VOLTAGE
Vd
30u
30d

FIG. 9

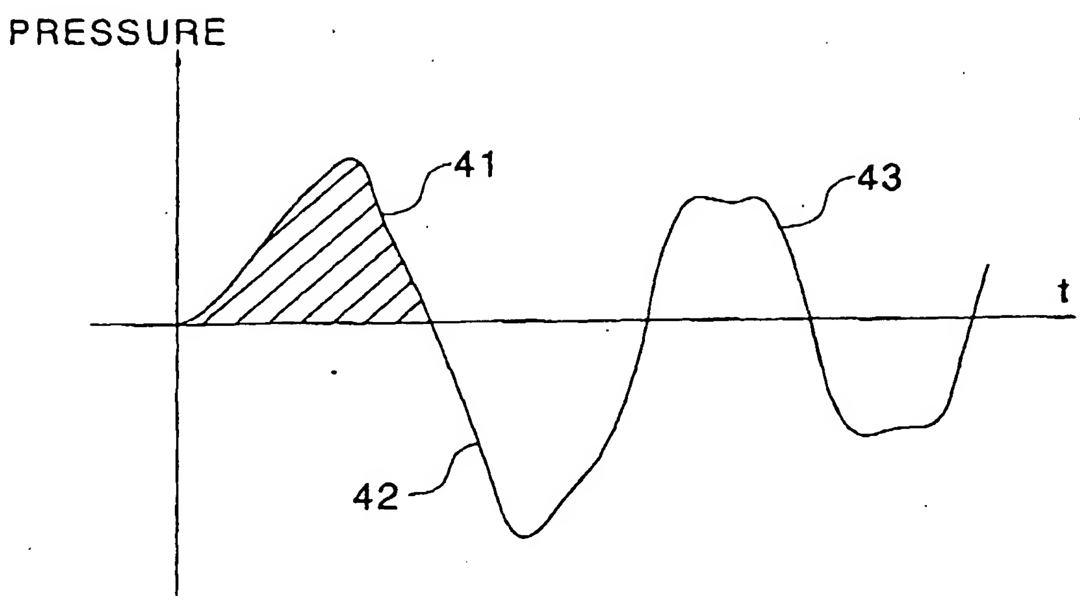


FIG. 10A

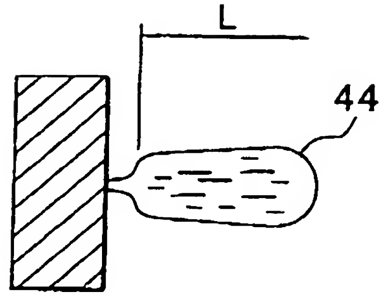


FIG. 10B

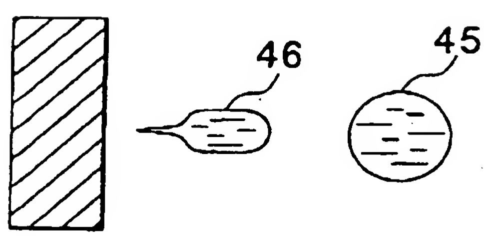


FIG. 11A

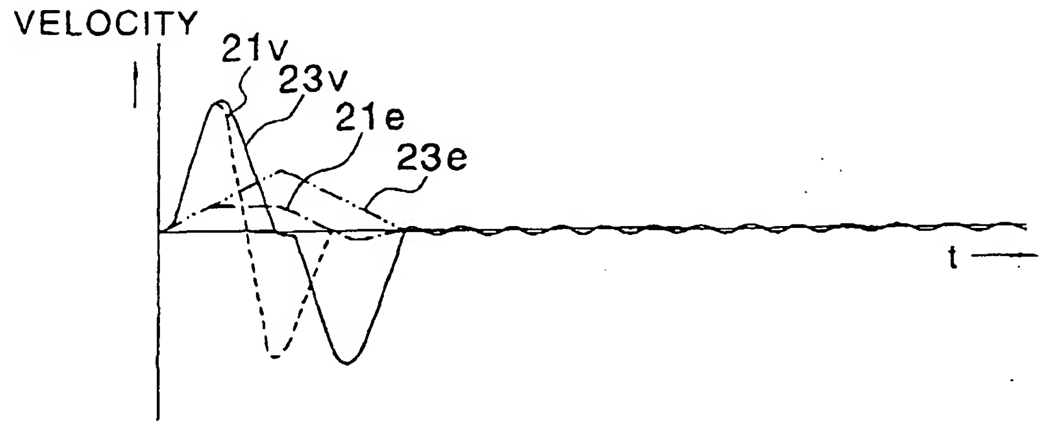


FIG. 11B

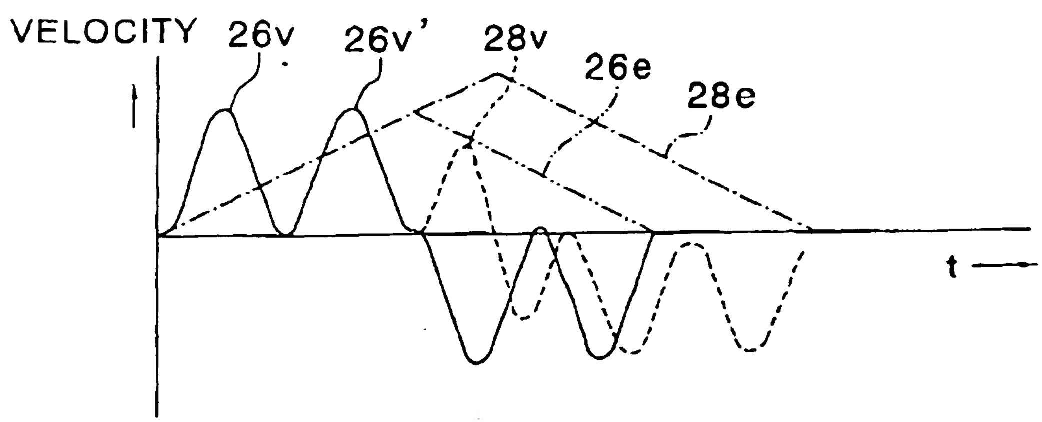


FIG. 11C

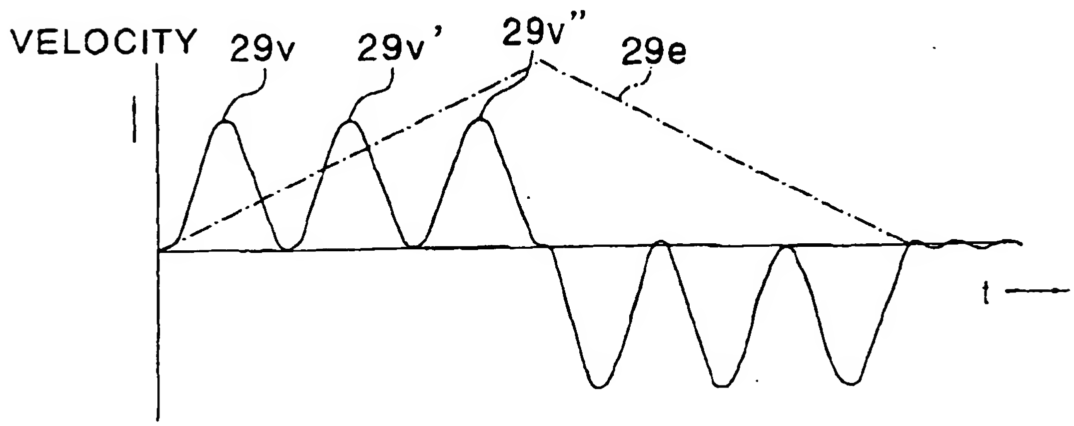


FIG. 12

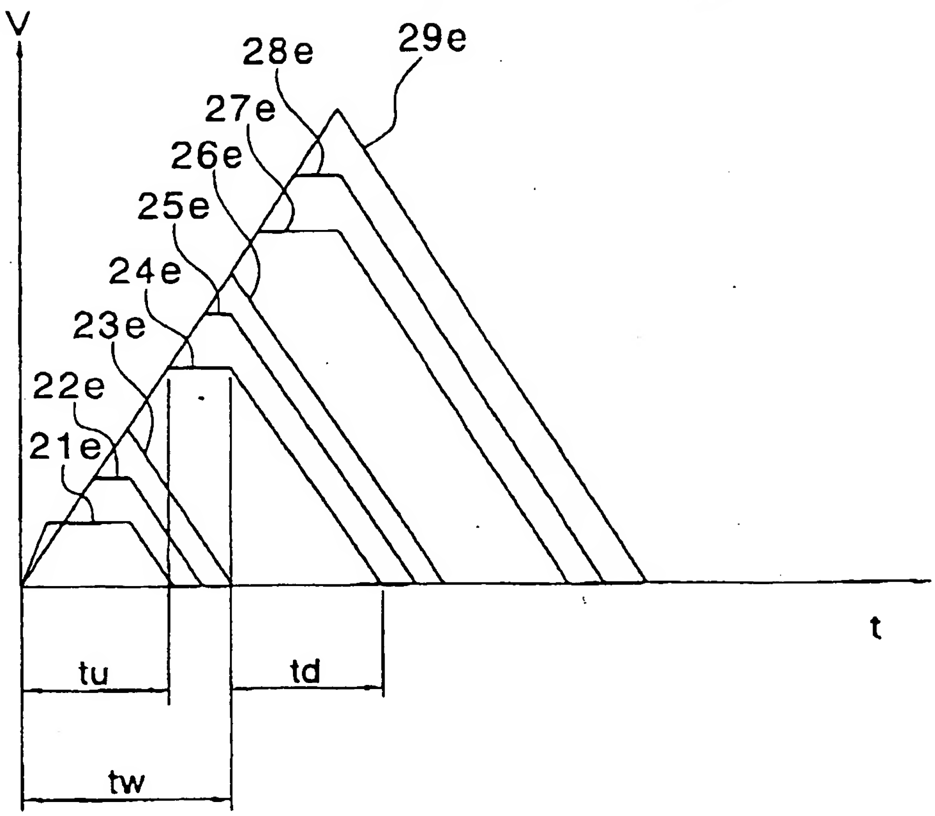


FIG. 13A

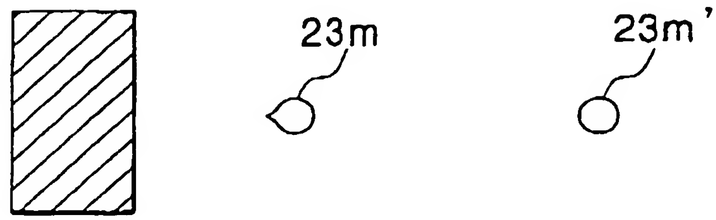


FIG. 13B

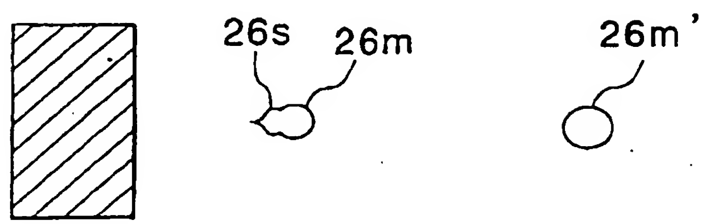


FIG. 13C

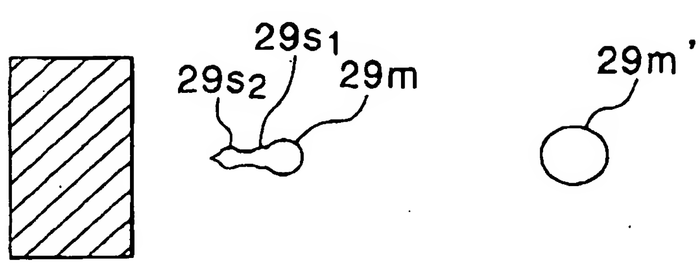


FIG. 14

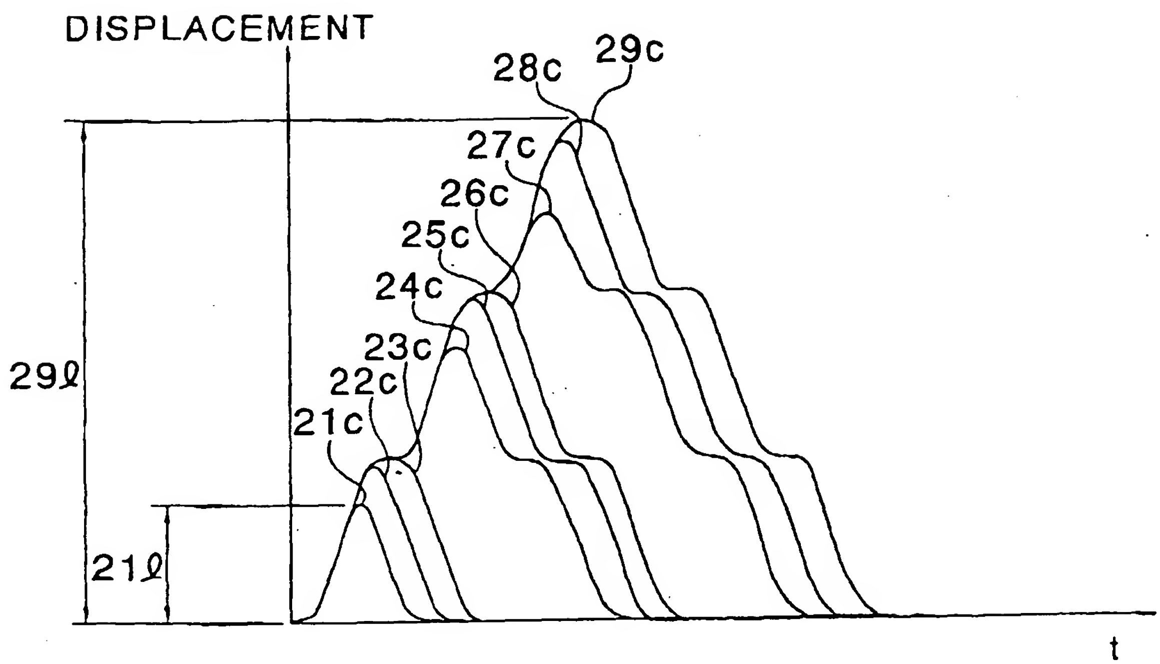
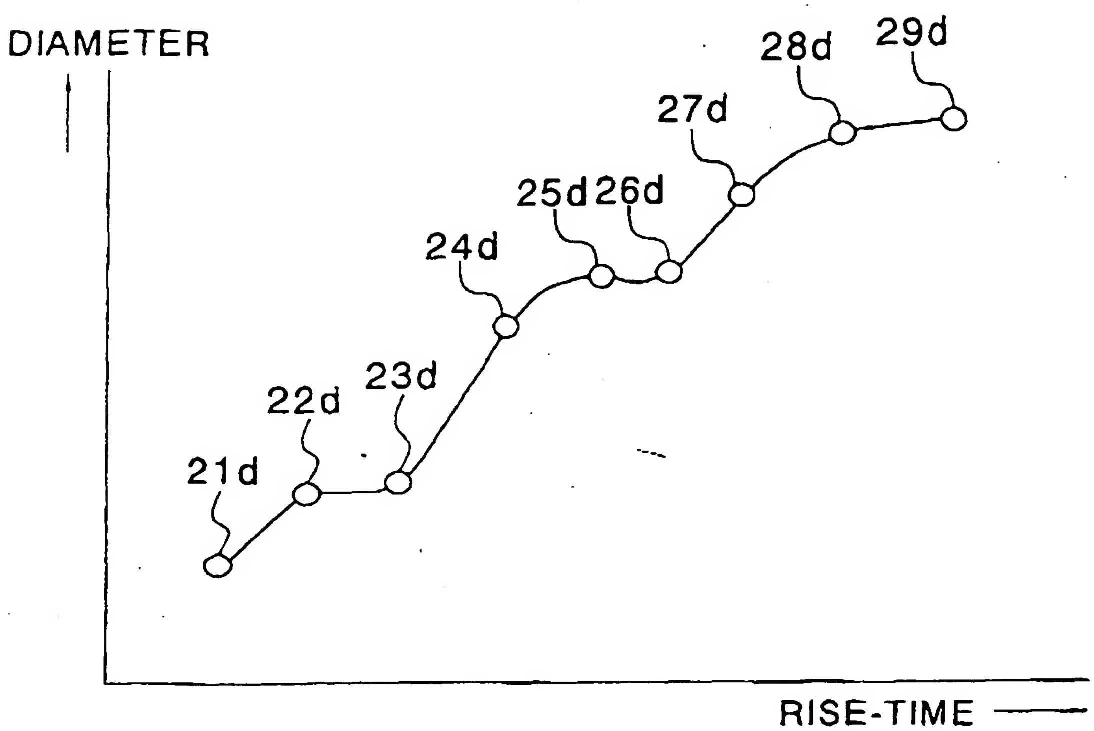


FIG. 15



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EUROPEAN SEARCH REPORT

Application Number
EP 98 12 4769

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X	WO 94 26522 A (COMPAQ COMPUTER CORP) 24 November 1994 * page 8, line 21 - page 11, line 3; figures 1,2 *	1-19	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
MUNICH	20 April 1999	Bridge, S

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EUROPEAN SEARCH REPORT

Application Number
EP 98 12 4769

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
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